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Dynamic modelling of a water-cooled blanket and energy storage options for a pulsed DEMO

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The Water-cooled Lithium-Lead (WCLL) blanket is one option under consideration for the EUROfusion DEMO programme. This blanket design must interface with the Primary Heat Transfer System (PHTS), Power Conversion System (PCS), and Energy Storage System (ESS) in an integrated solution to mitigate the pulsed power profile of the tokamak. The system must maintain an acceptable electrical output during the dwell period and minimise thermal and mechanical cycling of components. A complete transient model has been created, using the *Apros* simulation code, of the WCLL blanket, PHTS, PCS, and ESS, with heat transfer and thermal hydraulic phenomena described in one dimension. Simulation results show that the molten salt-based ESS succeeds in maintaining primary coolant temperatures as desired but significant pressure transients of over 2 MPa are induced. PCS transients also present challenges, as does system optimization to reduce the salt storage volumes required.

Keywords: DEMO, balance of plant, energy storage, pulsed operation

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1. Introduction

The pulsed operation of DEMO creates fundamental challenges for the primary heat transfer system and balance of plant. Although the thermal cycle and electrical power conversion systems may utilise precedented technology, their operation in a pulsed manner will not be straightforward, with the impact of frequent and significant cycling potentially detrimental to the lifetime of key components, such as heat exchangers, turbines and pumps [1].

If an energy storage system is needed there are constraints for a water-cooled system that stem from the low temperature of operation and the desire to use water-to-steam steam generators, leading to the proposal of a novel design utilizing molten salt [2]. To gain insight into the potential effectiveness of this concept, including quantification of plant transients it is necessary to simulate the time-variant behaviour of the possible heat transfer, power conversion and energy storage system. This paper details the development of a computer-based model to perform these simulations for the EU water-cooled DEMO concept.

2. System Parameters, Design, and Operation

The EU DEMO baseline design defines a reactor of ~2 GW thermal power output with a net electric output of ~500 MW delivered to the grid in pulses of ~2 hours separated by dwell periods of ~0.5 hours [3]. The water-cooled concept utilises a primary coolant of pressurised water at 15.5 MPa, with a reactor inlet temperature of 292°C and an outlet temperature of 325°C.

The WCLL blanket design [4] is essentially a set of modular boxes through which LiPb flows slowly to generate tritium. A set of coolant pipes carry water in a radial-toroidal direction to extract the heat deposited. The First Wall is integrated with each module, consisting of a Eurofer steel plate with water cooling channels.

For the modelled configuration in question, the First Wall and Breeder Zone are cooled in parallel, receiving and outputting coolant to common headers. Two coolant loops are assumed, each servicing one half of the total number of blanket modules with a cross connection, as shown in Fig. 1. Hence there is a single pressurizer, two steam generators, two hot legs, and two cold legs.

The energy storage system is provided by a molten salt loop in which salt is heated by a flow of hot water from the reactor outlet during a pulse. This hot salt is stored until the dwell, when it is fed back through the water-salt heat exchanger to heat cold water that now exits the reactor. Pipework directs cooling water from the heat exchanger to the steam generator or the cold leg. The system is sized to reduce the power transferred across the steam generators by 50% during the dwell.

To minimize the volume of salt needed it is necessary to maximize the temperature difference between the hot and cold tanks, increasing the thermal storage potential. It is also desired, to reduce transients and maintain maximal efficiency in the secondary cycle, to keep the maximum coolant temperature at its nominal value (325°C) throughout the pulse-dwell cycle. To achieve this, it may be possible to further heat the salt with thermal energy from the circulating LiPb. Such a scheme requires that coolant in the blanket modules not extract all nuclear heat deposited, allowing the LiPb to exit the rector at a higher temperature (~500°C) than it enters.

The power conversion system follows a PWR-type design with saturated steam generated at around 6.3 MPa, reheat provided by the main steam line, and multiple stages of feedheating. For DEMO, cooling of the divertor and vacuum vessel provide two lower temperature heat sources utilised as feedheating stages.

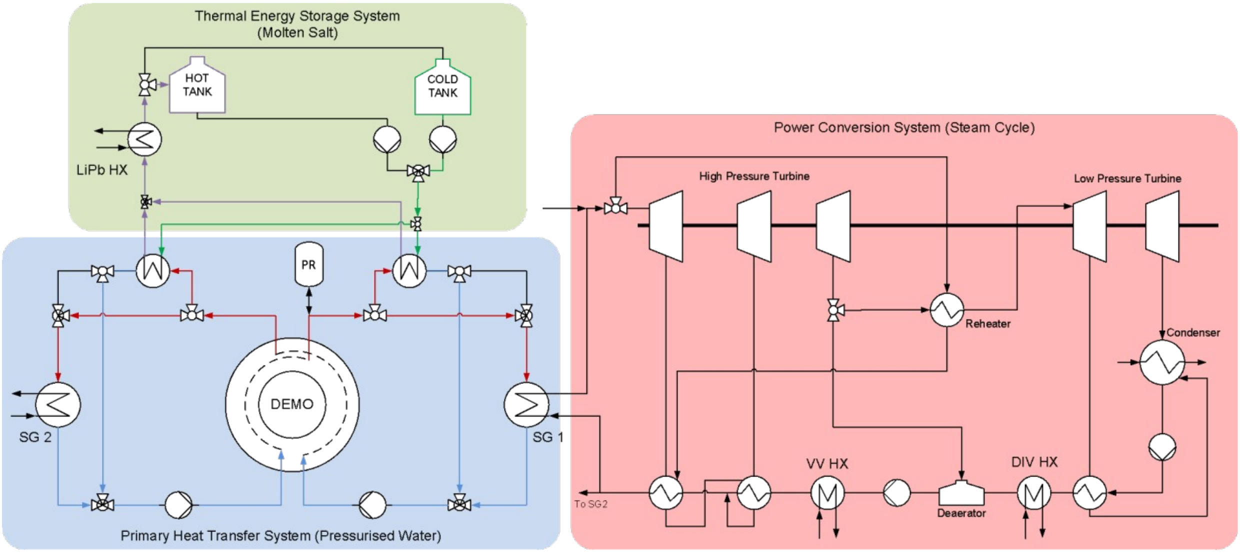

Fig. 1: Illustrative layout of reactor systems as modelled. Flows indicated assume on-pulse operation.

3. Description of the dynamic model

The model has been created using the *Apros Nuclear* software package. Contained within *Apros* are a number of fundamental components for the modelling of fluid systems and heat transfer, as well as components for control systems and electrical networks. All simulations are intrinsically dynamic with time-variant conservation equations solved in 1 dimension. For water/steam loops, a 6-equation model has been used, computing energy, mass, and momentum conservation for two distinct phases, while for the salt and LiPb loops, custom fluids were defined using a 3-equation, single phase, model.

3.1 Blanket model

The WCLL blanket module is inherently a complex flow structure, but its basic behavior can be captured in a 1-dimensional representation. LiPb flows from the back to the front of the module, then turns and flows in the other direction. Coolant tubes carry water along a radial-toroidal-radial path within the breeder zone and the side panels and first wall carry similar coolant channels. The module is divided into 6 sections toroidally by baffle plates, which lends a natural basis for the nodalisation in 1-D, shown in Fig. 2. The LiPb is further discretized into two nodes in a radial direction; the coolant pipes are discretized as shown and in thermal contact with the LiPb, into which power is deposited volumetrically to simulate nuclear heating. This scheme is repeated in two connected ‘layers’ which represent the flow of LiPb radially forwards and backwards through the module.

The first wall consists of a Eurofer steel plate divided into four radial nodes and six toroidal nodes, with power deposited into the front facing nodes only, and six water coolant channels nodes. The first wall is also in thermal contact with the LiPb in the breeder zone.

This basic blanket module model is repeatable, allowing each heterogenous module to be represented with differing dimensions, power deposition, and numbers of coolant pipes. One complication is that there are currently 630 individual blanket modules for DEMO and it is not practical to simulate them all. Instead, each set of identical modules at a particular poloidal position is represented by a single instance of the 1-D model, with appropriately scaled dimensions. Testing found differences in temperatures were less than 1% when comparing a single module and a collection of identical modules simulated in this way.

The modules are assumed to be serviced by coolant pipes that feed through the lower vessel port and exit through the upper vessel port, branching to each module in turn. The manifolds to each module are not currently represented in detail in the model but additional pressure drop coefficients could be added to account for their contribution to the flow characteristics.

3.2 PHTS, PCS and ESS models

Beyond the blanket model there is significant detail in the the modelling of all other loops shown in Fig. 1. The steam generators are of a standard U-tube design and represented using a pre-defined Apros component with 27 fluid nodes and 24 heat structure nodes. The water-salt heat exchangers are assumed to be of a standard counter-current shell-and-tube design with water on the tube side. The pressurizer is again a standard *Apros* component, subject to extensive validation [5], with 20 fluid nodes and a wall model.

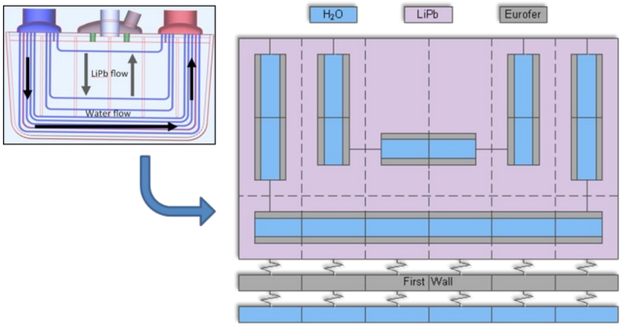

Fig. 2: Radial-toroidal view of 1-D nodalisation of WCLL blanket module (inset adapted from [4]).

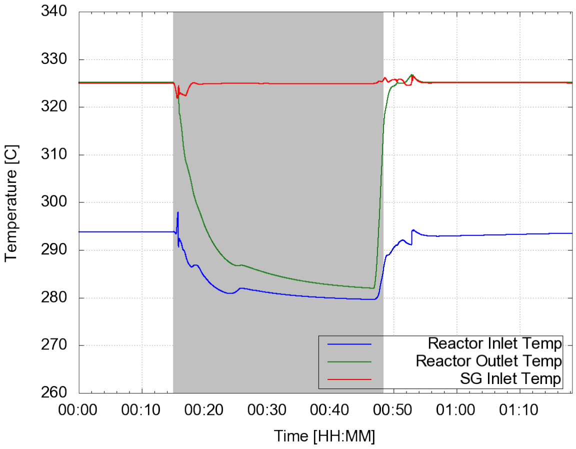

Fig. 2: PHTS coolant temperatures at selected points of one coolant loop (grey indicates the dwell period).

For the ESS, standard Apros pump models have been used and the LiPb-salt heat exchanger is assumed to be of a counter-current shell-and-tube design. The tanks can be simulated or set as fixed boundary points.

On the PCS side, a Stodola steam turbine model is used for each turbine stage shown in Fig. 1. Variations of shell-and-tube heat exchangers, both condensing and non-condensing, are used for the reheater, feedheaters, and condenser, and separated volume models are used for the moisture separation stage and deaerator.

Models of the divertor and vacuum vessel coolant loops have also been created, each featuring a pressurizer, pump, and heat exchanger. The divertor and vacuum vessel structures themselves are simplistically represented as large masses of steel through which coolant channels run, nonetheless giving an adequate representation of these components' thermal inertia.

To allow the overall system to function, it has also been necessary to define and integrate a number of control systems. These include 3-input controllers for controlling the steam generator and condenser water levels, turbine admission valve control, and a system for controlling the water flow path through the primary coolant loops and the flow of hot and cold salt. This latter system must monitor the reactor outlet temperature and divert more (or less) water via the water-salt heat exchanger, together with more (or less) hot or cold salt, in order to maintain the steam generator inlet temperature as the reactor transitions between pulse and dwell. Other control systems define pressurizer heater and spray functions, coolant flow rates, and under/over pressure actions in the PCS.

4. Results

The model was run for a simulation time of 15 minutes before a dwell was initiated. Coolant temperatures show that the system works as intended, with the steam generator inlet temperature maintained throughout the dwell (Fig. 3). However, the physical geometry of the PHTS means this does not equate to a constant average coolant temperature. In the dwell period, large sections of the hot leg, once hot, now contain cooler water, as do the blanket modules themselves. This cool-down of large volumes of coolant leads to contraction and a drop in pressure to around 14 MPa as a result (Fig. 4). Flashing of steam in the pressurizer resists the change but the outsurge is too large to maintain a constant equilibrium pressure. The heater cannot supply enough power to compensate within the timescales necessary (and remains manually switched off in Fig. 4).

Of additional concern is a large and rapid pressure spike at the start of the next pulse. Fusion power is assumed to ramp up in 100 s and this leads to a large in-surge of sub-cooled water to the pressurizer in a short space of time. In the current model, however, this cooler water does not break the surface of the pressurizer water volume, leaving significant stratification and saturated water in contact with the steam volume. Condensation effects are then insufficient to reduce the pressure on the timescales required and the pressure reduction that does eventually occur is largely due to the operation of the spray line only. The stratification is an important effect in determining the peak pressure and will be further investigated through interrogation of the model.

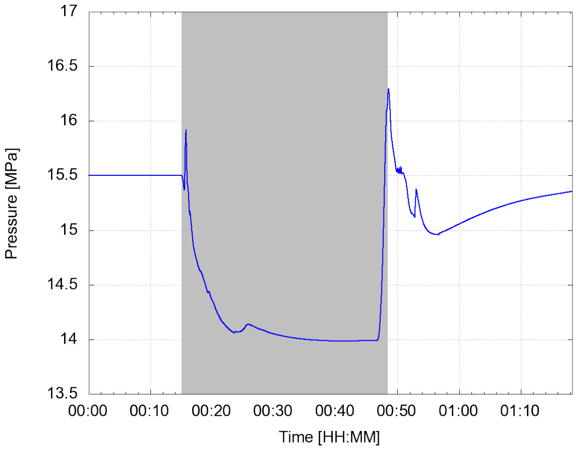

Fig. 2: Coolant pressure in the PHTS as measured at the pressurizer (grey indicates the dwell period).

The intended hot salt temperature is 326°C; however, in the simulation, during a pulse, the salt is only heated to 321°C. This would increase the necessary salt volume to 21 907 m^3 and restrict the temperature of the coolant to below 321°C during the dwell (in Fig. 3 the hot salt temperature was artificially fixed at 326°C). The difficulty in heating the salt is firstly a result of narrow pinch points in the water-salt heat exchangers, which will require larger heat transfer areas and hence large components, and secondly due to insufficient heating from the LiPb. The nominal system design required a 196°C increase in temperature for the LiPb on its exit from the reactor, however, only 77°C was achieved (Fig. 5). The cooling of the LiPb in the blanket modules can therefore be considered too efficient and it would take a reduction in either heat transfer area (through the number of pipes) or the heat transfer coefficient in order to achieve the desired operation. It is also seen in Fig. 5 that the LiPb outlet temperature varies slowly and there is significant time before the maximum level is reached at the start of a new pulse. This again challenges the effectiveness of the proposed strategy since less energy is transferred to the salt during this period.

At steady operation during a pulse the gross electrical output power is 713 MW, falling to 358 MW at its lowest during the dwell (Fig. 5). While the ramp up on return to pulse is relatively smooth, the initial drop in power at the end of a pulse is quite sharp (~220 MW/min

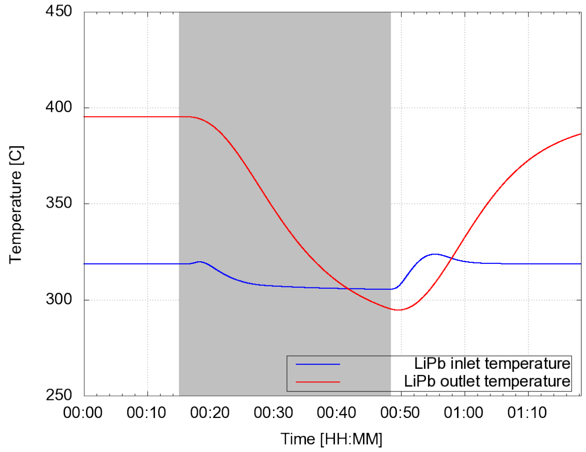

Fig. 2: Temperatures of the circulating LiPb (grey indicates the dwell period).

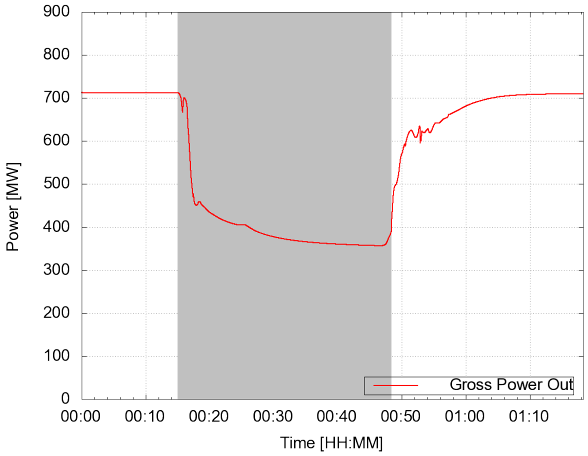

Fig. 2: Gross electrical output measured from the generator (grey indicates the dwell period).

at its maximum). Current typical grid codes state a maximum rate of change of 50 MW/min, though this may be relaxed for a demonstration power plant operating in future grids that will already accommodate a high proportion of intermittent renewables.

The model allows for inspection of a great number of results, not all of which can be shown here. This includes pressure transients in the shell side of the feedheaters, of up to 1.0-1.5 MPa between pulse and dwell, and the temperature distribution of the First Wall, the front face of which (for the equatorial outboard module) drops in temperature by 250°C, while its average temperature falls by almost 100°C. Both of these issues are additional concerns in terms of cycling.

5. Conclusions

A fully dynamic model of all blanket, divertor, and vacuum vessel structures, primary coolant loops, the energy storage system, and steam cycle for a water-cooled DEMO has been created. The molten salt-based ESS has been shown to work in principle; however, there are a number of issues that must be resolved. Achieving the desired heating of the molten salt during the pulse is challenging due to the requirements it places on the water-salt heat exchanger design and the limits to which the LiPb can be employed as an additional heating source with the current blanket design. At its nominal design point, the system requires ~20,000 m^3 of molten salt and further increases to this figure are unwelcome.

Maintaining a constant steam generator inlet temperature does not address the wider cool-down of primary coolant throughout the circuit, which leads to significant pressure transients that affect all components in the blanket/PHTS system. Meanwhile, though the gross electrical output may eventually be acceptable, this belies other significant temperature and pressure transients in the PCS, PHTS, and blanket that must be considered further. Finally, we note that with extensive manipulation of the flows through the ESS and PHTS, the system has a degree of complexity that would not be present with an alternative solution, such as an intermediate salt storage loop positioned between the PHTS and PCS. This complexity can only be justified if satisfactory issues to the above issues can be found.

Acknowledgments

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